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FINAL REPORT:

MERRIMACK RIVER PROJECT

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FINAL REPORT

NATIONAL OCEAN SERVICE/U.S. ARMY CORPS OF ENGINEERS, NEW ENGLAND DIVISION MERRIMACK RIVER PROJECT

I.   INTRODUCTION

The Merrimack River Project, a cooperative effort between the National Ocean Service (NOS) and the U.S. Army Corps of Engineers, New England Division (CENED), was one of three projects undertaken in 1989 to update or establish tidal datums for CENED project areas. This project was accomplished through the Fiscal Year 1989 Work Order approved by NOS and CENED (Appendix 1).

The purpose of the Merrimack River Project was to update the tidal datum control network along the Merrimack River, in northeast Massachusetts, from the mouth of the river at Plum Island upriver to Haverhill. The network was updated by the Sea and Lake Levels Branch, National Ocean Service (NOS) through tidal datum computation from data collected through the installation and operation of tide stations at five locations along the river. This network is required by the U.S. Army Corps of Engineers, New England Division (CENED), to support maintenance dredging of the river navigation channel.

II.   BACKGROUND

The project area and station locations are shown in Figure 1. Details of the river channels, soundings and channel locations are contained in NOS Nautical Chart 13274 and U.S.G.S. topographical quads for Newburyport East, Newburyport West, and Haverhill. Additional CENED project information is contained in Appendix 3.

Tidal datum information at Plum Island and Newburyport was last determined in 1953 and 1954 and needed updating to the latest tidal datum epoch. New data needed to be collected upriver of Newburyport.

III. PLANNING

A. Information Review

NOS planned the operational components of this project after input from CENED and review of information sources on the water level variability and tidal characteristics in the river. Items reviewed were tidal data summaries in NOS files, NOS Tide Tables (1989) and Nautical Charts, USGS topographic maps, the NOS Coast Pilot (1989), and USGS extreme water levels on the river.

The purpose of the review was to obtain an understanding of the changes in tidal characteristics of the river within the project area and an understanding of the possible highest river levels that might be expected. It was learned that no tidal observations had ever been made by NOS or CENED upriver of Newburyport. This resulted in significant uncertainty about the range and time of tide along approximately two-thirds of the project area.

B. Determination of Station Locations

The preliminary selection of the station locations was based on the information review and the location of historical stations. A network of stations was selected to provide spatial coverage of estimated variations in tidal characteristics and to reoccupy historical stations so that datums could be recovered and changes monitored. Total coverage of stations was designed such that changes in tidal characteristics would be effectively measured and interpolation of tidal characteristics and tidal datums between locations could be accurately determined. The ease of level connection to the National Geodetic Vertical Datum (NGVD) bench mark network and availability of stable gauge installation structures were the primary considerations for the stations upriver of Newburyport.

The station location planning included the establishment of a secondary station (minimum of 1 year of operation) at Newburyport to measure the seasonal water level variations during the survey period. The secondary station also provides control for datum computation at nearby tertiary stations (minimum of 1 month of operation). The long term NOS station at Portland was used for the primary control station (minimum of 19 years of operation) to provide control for datum determination at all stations.

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Four tertiary station locations were selected: one on Plum Island at the river entrance and three between Newburyport and Haverhill. Table 1 is a listing of station information. Copies of station documents are contained in Appendix 4.

Table 1 STATION LOCATIONS AND INFORMATION

Station Number	Name	Latitude	Longitude	Date Installed	Date Removed	Series Length	Marks Estab.	Recov. Marks	Distance Leveled
8440273	Salisbury Point	42/50/3'N	70/54.5'W	5/18/89	10/24/89	7-9/89	1	4	0.96 KM
8440369	Merrimacport	42/49.5'N	70/59.3'W	5/19/89	10/20/89	9/89	3	2	1.25 KM
8440452	Plum Island	42/49.0'N	70/49.2'W	5/25/89	10/25/89	6-9/89	3	2	0.44 KM
8440466	Newburyport	42/48.7'N	70/51.9'W	5/17/89	9/11/90	6/89-5/90	3	3	1.62 KM
8440889	Riverside	42/45.8'N	71/04.6'W	5/23/89	10/24/89	6-9/89	2	3	1.60 KM

IV. STATION INSTALLATION, OPERATION, AND REMOVAL

A. Station Reconnaissance

With assistance from headquarters personnel, Atlantic Operations Group (AOG) personnel made a reconnaissance of the project area in March 1989. Activities included a review of historical station locations, bench mark and NGVD information, procurement of supplies and equipment, repair of existing equipment, and preliminary installation plans. Specific gauge locations were selected; notes and sketches of each site were made, including stilling well lengths, number and type of brackets required and length of tide staffs. Historical bench marks were recovered and the number and location of new marks were determined. Permits were filed with the Department of Public Works for the two installations on highway bridges. The CENED provided updated information to NOS on the location and NGVD elevations of bench marks not in the NOS files.

As a result of the reconnaissance, it was determined that a stilling well installation would not be feasible at the Plum Island location. The pier structure had insufficient access and water depth. Due to the critical need for data from this location, a 'bubbler' pressure

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gauge installation was planned. Contact was made with the U.S. Coast Guard to request permission to install the gauge at the abandoned Auxiliary building and the staff on the abandoned Coast Guard pier. There was also some doubt about an ADR installation being able to record all low waters at Merrimacport when summer river levels were low due to the shallow water at that location. An ADR installation was planned with the intention of possible addition of a bubbler gauge to measure low waters after review of initial data.

B.   Station Installation and Levels

The five project stations were installed during May 1989. The station components were a tide gauge, tide staff, and a network of five bench marks. The station configurations and equipment used at each location were essentially the same. The ADR gauges used were Fischer-Porter Model 1551 gauges enclosed in steel waterproof covers with cast aluminum base plates. These gauges are float driven and produce a punched-paper-tape output using a 6-minute timer. The bubbler pressure gauges were Metercraft Model 7602 nitrogen pressure driven gauges with analog pen and ink strip chart outputs. All gauges were tested and calibrated in the AOG gauge shop in Norfolk, VA prior to installation.

The stilling wells were made of 6-inch diameter Schedule 40 PVC of appropriate lengths, with a PVC flange glued to the top and an adaptor orifice glued to the bottom. Some of the wells had additional slotted shrouds attached to the lower end to minimize the draw down effects of high speed water currents. An aluminum adaptor was used to join the top flange and gauge base plates. Stilling wells were secured to pilings or bridge fenders with stainless steel long arm or face clamps and stainless steel lag bolts. Two or three clamps for each well were typically required.

The bubbler orifice at Plum Island was mounted on a piling of the pier structure. The tubing to the gauge box at the USCG Auxiliary Building was buried in the sand . The bubbler orifice at Merrimacport was banded to a steel pipe that had been driven into the bottom near the floating dock. The tubing to the bulkhead and the gauge box was held in place by rocks.

The tide staffs were made of 3-foot sections of vitrified steel scales, graduated in tenths of feet, and screwed to a backing board. A brass angle iron was screwed to the backing

board, usually at a whole foot mark, to serve as a staff stop for leveling. The staff backing boards were secured to pilings or stringers with stainless steel lag bolts. Dive teams were used to secure staffs, stilling wells, and bubbler tubing and orifices below the water line. At the two bridge locations, Mr. Gordon Broz of the Department of Public Works provided information on the construction of the bridge fenders and made recommendations for locating the staffs and wells. Strong ebb and flood currents demanded extra care in the diving operations.

Bench mark establishment and leveling procedures used for this project followed NOS standards and procedures (Hicks et al, 1987). New bench marks were set at each station so the local network consisted of a minimum combination of five historical and new marks. New bench marks were set in concrete structures or bedrock. Written descriptions and location sketches were prepared for all new bench marks by the field teams. Table 1 also provides bench mark and leveling information for each station.

Second Order, Class 1 levels were run between the tide staff stop and the local bench mark network upon installation and removal at each station. Three or four persons comprised the leveling crew. Removal levels at each station were used to verify vertical stability of the tide staff and bench marks. The leveling served to bracket the time series used for datum determination with vertical stability checks.

C.   Station Operation

Local contract tide observers were hired and trained by the field team upon gauge installation. The observers recorded gauge time checks and tide staff readings a minimum of three times per week and notified the local AOG route person of gauge malfunctions. The AOG route person was responsible for removing the gauge records at the end of each month, scanning them for major problems, and forwarding them immediately to headquarters for processing.

During a second preliminary scan or during subsequent processing steps by Tidal Analysis Section personnel, data problems due to gauge malfunction or tide observers were forwarded to the AOG route person via telephone and mail. Corrective maintenance was then performed, resulting in minimal data defects and few severe breaks in data. The tide observers were generally quite reliable.

All stations except Newburyport were removed in October 1989. Newburyport remained in operation until September 1990, when it was removed in conjunction with the removal of four FY90 NOS/CENED project stations south of Boston.

V. DATA PROCESSING AND DATA QUALITY

A. Data Processing

The data from all stations were processed and tabulated using NOS standard operating procedures. These procedures include a preliminary evaluation of data quality using a visual scan and the completion of a comparative reading by a data analyst for each monthly record. The comparative reading uses the tide observer's staff readings and the simultaneous gauge readings to establish a statistical staff-to-gauge relationship, i.e. the setting that is applied to the time series before tabulation. This transfer of gauge readings to the staff results in the tabulated heights being referenced to tide staff zero at each location.

The punched-paper-tape 6-minute data records were translated onto magnetic tape in a batch mode using an optical reader. The data was then loaded onto a mini-computer system for processing and analysis using the Automated Tidal Data Processing System (ATDPS) software.

The 'bubbler' analog strip chart records were corrected for time errors if necessary and then digitized using a manual digitizing system. The discrete hourly heights and the times and heights of the high and low waters were manually selected, digitized, and loaded onto a micro computer file. These preliminary tabulations were then transferred onto the mini-computer system via telecommunications for processing and analysis using ATDPS.

ATDPS is a set of interactive software routines used by data analysts to produce the monthly tabulated output products of hourly heights, the time and heights of the high and low waters, the monthly mean values of various tidal datums and datum relationships, and the extreme tides for the month. Appendix 5 is an example of a typical monthly tabulation for a Merrimack River Project station.

ATDPS allows for editing and gap-filling of the 6-minute data as required and editing and break-filling of the hourly heights and high and low waters. The analyst uses a combination of computer program diagnostics and their knowledge of tidal characteristics and gauge operation to make decisions on the manipulation of data. Graphical comparisons with predicted tides and time series from nearby stations are used to identify and deal with anomalous situations. Data editing and interpolations are performed using prescribed standard operating procedures.

The monthly means produced during the tabulation process are used in the tidal datum computation procedures. All work performed during the tabulation process is verified by a senior oceanographer prior to submission for datum computation. A descriptive outline of the tabulation procedures is found in the Manual of Tide Observations (NOS, 1965).

B. Data Quality

NOS uses statistical information to quantify and assess data quality for the data records. The classification of weeks and months of data as valid, substandard, or invalid are found in Tables 2 and 3, and provide summary data quality statistics for the Merrimack River Project. Table 2 is the monthly data classifications for each station and Table 3 is the monthly and cumulative statistics for the classifications. The statistics in Table 3 are graphed in Figure 2.

The data quality from this project was considered to be good, with less than 13 percent of the data classified as invalid. The data collected enabled datums to be established for each location. The most serious problem, as indicated in Table 2, was due to the shallow water problem at Merrimacport resulting in the recording of invalid flat low waters for the first three months. The stilling well was then lowered and a bubbler gauge installed enabling the collection of one and a half months of valid low waters until the gauges were removed. The one month of invalid data at Salisbury Point was due to a gauge malfunction and the lack of observer checks for the last week in May and the first two weeks in June 1989. Much of the substandard ADR data was due to stops and restarts, punch mechanism hang-ups, paper tape hang-ups, and observer time reset problems. The typical substandard data from the bubbler gauges were due to severe timer drifts, time resets and problems with the pen and ink mechanisms.

Table 2 DATA QUALITY CLASSIFICATIONS

STATION NUMBER	1989 JUN	JUL	AUG	SEP	OCT	NOV	DEC	1990 JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
8440273	I	V	S4	S2											
8440369	I	I	I	S3											
8440452	V	S1	S1	S3											
8440466	S3	V	V	S1	S1	V	S1	V	S1	S1	V	V	V	V	V
8440889	V	V	S1	S3											

KEY

V = VALID
Sx = SUBSTANDARD FOR x WEEKS
I = INVALID

Table 3 DATA QUALITY STATISTICS

DATA SET	DATA WEEKS	NUMBER/PERCENT OF WEEKS VALID	SUBST.	INVALID
JUNE	20	9/45.0	3/15.0	8/40.0
JULY	20	15/75.0	1/05.0	4/20.0
AUGUST	20	10/50.0	6/30.0	4/20.0
SEPT.	20	8/40.0	12/60.0	0/00.0
10/89-8/90	44	40/90.9	4/09.1	0/00.0
Overall:	124	82/66.1	26/21.0	16/12.9

VI. DATUM COMPUTATION

NOS used established procedures (Marmer, 1951 and Swanson, 1974) to compute tidal datums at each station in the Merrimack River Project. Tidal datums are local reference elevations defined in terms of a certain phase of the tide (Hicks, 1989) measured at a specific location. The tidal datums are computed from the monthly tabulation of the high and low waters and the hourly heights. Monthly mean values of Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Sea Level (MSL), Mean Low Water

(MLW), and Mean Lower Low Water (MLLW) are computed directly in the tabulation process. From these mean values, additional monthly mean values of Mean Range (MN), Great Diurnal Range (GT), Diurnal High Water Inequality (DHQ), and Diurnal Low Water Inequality (DLQ), Mean Tide Level (MTL), and Diurnal Tide Level (DrlTL) are derived (Hicks, 1989). Reference is again made to Appendix 5 for an example of a tabulation listing of these monthly values.

For purposes of obtaining an accepted mean value of a tidal datum, NOS uses the concept of a primary determination. A primary determination of a tidal datum is one that is derived from 19 years of observation. The 19 year period constitutes the time period during which all significant astronomical tide-producing forces will have completed full cycles, such as the Node Cycle and Metonic Cycle (Hicks, 1989). NOS designates a specific 19 year period as the National Tidal Datum Epoch (NTDE), with the present epoch being the 1960 to 1978 time period. Accepted tidal datums for the primary control station at Portland have been computed from observations over the 1960-78 NTDE.

Accepted mean values of tidal datums are defined in terms of a NTDE. Since it is impractical to operate all required stations for such a long time period, the equivalent datums must be computed. NOS computes equivalent 19-year mean values for subordinate stations with shorter series of observations by the method of comparison of simultaneous observations. For the Merrimack River Project, the equivalent mean values for the secondary station at Newburyport were computed through comparison of 12 months of mean values with the 19-year control station at Portland. The equivalent mean values for the tertiary stations were then computed through comparison of 1 to 4 months of mean values with the secondary station at Newburyport. Appendix 6 is an example of a comparison of simultaneous observations for a typical Merrimack River station.

Datum computation methodology requires similarity between stations in tidal characteristics and similarity in water level variations on monthly, seasonal, and yearly time scales. Long term trends in relative mean sea level must also be similar at both control and subordinate locations. These criteria for datum computation led to the exclusion of the month of June 1989 at Riverside for use in datum computation due the local effects of high river flow.

Table 4 provides the preliminary tidal datum elevations relative to MLLW and the equivalent mean values for the other tidal parameters for each of the project stations. Appendix 7 provides the published bench mark sheets for each station and the elevations of each bench mark relative to the various tidal datums.

Three particular notes must be made regarding the NGVD connections for this project. The station at Plum Island has no level connection to NGVD; the nearest NGVD marks were near the airport along Water Street. An estimated value for NGVD was derived from the MTL-NGVD relationship at the Salisbury Beach historical station, adjusted for the changes in datums between the 1941-59 and 1960-78 epochs using the known change at Boston. The NGVD value at Salisbury Point is based on elevations of two marks that are part of the Massachusetts Geodetic Survey (MGS). The NGVD value at Merrimacport is based on the elevation of only one MGS mark. The National Geodetic Survey (NGS) has not accepted the MGS elevations, and the NGVD relationships at these stations will not be published by NOS and should be used with caution.

The equivalent mean values of the datums computed through the comparison of monthly means procedure provide an approximation of the values computed directly from 19 years of data. The generalized one-standard deviation accuracies of tidal datums in non-river situations on the East Coast, have been estimated to be 0.13 foot for one month series and 0.10 and 0.05 foot for three and twelve month series respectively (Swanson, 1974). Datums for this project were based on series of one to twelve months in length. The series lengths used for each station are found in Table 1.

Table 4 TIDAL CHARACTERISTICS - MERRIMACK RIVER

STATION NUMBER	HWI	LWI	MHHW	MHW	DRLTL	MTL	MSL	NGVD	MLW	MLLW	DHQ	DLQ	MN	GT
8440452	4.06	10.26	8.77	8.35	4.38	4.33	4.34	3.81*	0.31	0.00	0.42	0.31	8.04	8.77
8440466	4.11	10.65	8.76	8.31	4.38	4.28	4.27	3.44	0.24	0.00	0.45	0.24	8.07	8.76
8440273	4.45	10.99	8.42	7.96	4.21	4.08	4.12	2.99*	0.20	0.00	0.46	0.20	7.76	8.42
8440369	4.97	11.82	7.80	7.31	3.90	3.75	3.82	2.32*	0.19	0.00	0.49	0.19	7.12	7.80
8440889	5.42	0.83	6.12	5.66	3.06	2.90	2.72	0.61	0.13	0.00	0.46	0.13	5.53	6.12

* preliminary values

VII. DATA ANALYSIS

A.   Mean Values

A detailed comparison of the Greenwich mean high and low water intervals (HWI & LWI) and other parameters in Table 4 is used to study the characteristics of the tide in tidal rivers. A time difference of 2.99 hours exists between the time the low waters reach Plum Island and the time they arrive at Riverside. The time of transit for the high waters is only 1.36 hours. The duration of rise of the tide at Plum Island is 6.20 hours, typical for a station on the coast. However, the duration of rise at Riverside is a mere 4.59 hours, showing that, in effect, the high waters are accelerated and the low waters are retarded moving upstream in the river. Figures 3 and 4 are simultaneous plots of hourly height time series from the three stations along the river. The plots clearly show the differences in time of tide and durations of rise and fall of tide. The sinusoidal shape of the incoming tide curve becomes increasingly distorted upstream due to frictional effects of the shallow water and the river bed. The tidal characteristics of Plum Island and Newburyport are very similar with major changes in time and range of tide occurring upstream of Newburyport. These two stations are located near the entrance to the estuary that has extensive tidal marshes and exposed mudflats at low tides. Upstream from Salisbury, the estuary (and the tide) is constricted to a river channel through the uplands and hill country.

B.   Harmonic Analysis

Traditional harmonic analysis procedures provide insight into the response of the tide to shallow water and other frictional effects. NOS harmonic analysis procedures (Schureman, 1958) solve for or derive pre-determined sets of harmonic constituents depending on the length of series. The analysis assumes that the observed tide curve can be treated as a complex waveform that can be expressed as the sum of a number of cosine curves, whose amplitude and frequency may vary slowly with time (Admiralty Manual, 1969). Each component curve used is due to a specific component of the earth-moon-sun orbital tide-producing interaction. The outputs of the analyses are sets of harmonic constant amplitudes and phases for each harmonic constituent solved for.

A set of harmonic constants has been compiled for each station based on 29-day harmonic analyses (Dennis and Long, 1971), and are provided in Appendix 8. Table 5

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provides the amplitudes and phases derived from a set of simultaneous 29-day harmonic analyses run for each station. The constituents K1 and O1 express the response of the water level to the moon's diurnal tide producing forces which vary with the moon's monthly declinational cycle. The constituents M2 and S2 express the response of the water level to the moon's semi-diurnal tide producing forces which vary with the moon's spring tide/neap tide monthly cycle. The constituents M4 and M6 are called higher harmonic constituents with quarter-diurnal and sixth-diurnal frequencies, respectively. They express the effects of shallow water and friction of the river estuary on the incoming tide. The constituents tabulated are the most significant constituents found in the analysis, and their amplitude and phase relationships at each location determine the shape and variation of the tide curve with time.

As expected for the strongly semi-diurnal tide found offshore and in the Gulf of Maine (Redfield, 1980), the amplitude of the M2 constituent at each location is at least seven times larger than the amplitude of any other constituent. The amplitude of M2 and S2 decrease and the M2 and S2 phases increase as one proceeds upriver, and illustrate the damped-progressive wave nature of the tide after passing through the entrance at Plum Island from the shelf. The amplitude and phases of the K1 and O1 constituents show similar trends, but to much lesser degrees. The longer period (and wavelength) diurnal constituents are not as affected by the topography and friction as the shorter period semi-diurnal constituents. The amplitude of the shallow water constituent M4 increases from near zero at the entrance to 0.46 foot at the station furthest upriver. The M4/M2 ratio increases from near zero to 0.18. The amplitude of the M6 shallow water constituent changes very little from the entrance, but remains significant just below 0.10 foot. The M4 and M6 amplitudes and phases, and their relationship to the amplitudes and phases of the other constituents, are mainly responsible for the changes in the shape of the tide curve proceeding upriver shown in Figures 3 and 4. The values of the harmonic constants found in Table 5 are consistent with the interrelationships of the mean time intervals, datums, inequalities and ranges of tide found in Table 4.

C.   National Geodetic Vertical Datum Relationships

Figure 5 shows the relationship of the tidal datums to NGVD proceeding upriver (see also Table 4). The relative rise in elevation of the tidal datums referenced to NGVD is common in large tidal rivers. The figure illustrates the limitations of extrapolating relationships of NGVD to tidal datums from one particular measurement location to

Table 5   HARMONIC CONSTANTS

CONSTITUENT AMPLITUDES, H (FEET) AND PHASES, K' (DEGREES)

Station	K1 H	K1 K'	O1 H	O1 K'	M2 H	M2 K'	S2 H	S2 K'	M4 H	M4 K'	M6 H	M6 K'	M4/M2 RATIO
0452	.45	140	.34	123	3.82	331	.53	000	.02	198	.09	263	.006
0466	.44	147	.35	129	3.82	338	.51	011	.15	231	.09	294	.039
0273	.42	157	.34	137	3.57	348	.47	023	.13	249	.09	342	.036
0369	.39	170	.32	149	3.19	005	.40	043	.21	282	.13	037	.065
0889	.36	196	.29	165	2.54	031	.30	075	.46	360	.07	038	.181

another location in the Merrimack River. Slopes in tidal datums relative to geodetic datum are to be expected from outer coastlines, in through inlets, and upstream in rivers and estuaries. Extreme care must be used in any extrapolation or interpolation because the relationships change significantly over short distances.

D.   Effects of River Flow

The Merrimack River has active river flow throughout the year, with higher river flows occurring in the spring season weather patterns and in response to shorter term storm events. The effects of this river flow during the time period of the observations are integrated into the mean values of the tidal characteristics and harmonic constant values found in Tables 4 and 5.

Figures 6a and 6b are comparisons of monthly mean sea level and monthly mean range of tide between the control station at Portland and the secondary station at Newburyport over a 14 month period. The monthly mean sea level values are plotted relative to NGVD to further illustrate the slope in mean sea level datum relative to geodetic datum from outside to inside. The mean sea level and range of tide variations over the time period plotted are very similar, with differences due mostly to the effects of changes in river flow on the tide at Newburyport. The similarities between stations are important for the effective use of Portland as a primary control station in datum determination in the Merrimack River.

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The effects of the weekly and daily variations in river flow (USGS, 1989) are illustrated in Figures 7 and 8. In Figure 7, the variations in daily mean sea level at Riverside, the station furthest upriver, are highly correlated with the daily variations in river flow. The variations in daily mean sea level further downriver at Newburyport are not highly correlated with daily river flow for these two short term events. The episodes of high river flow were due to the passage of a series of low pressure troughs accompanied by moderate rainfall from June 6 through June 17, 1989 (National Weather Service, 1989). The effects of the high river flow on the daily variation in the tide are illustrated in the hourly height plots in Figure 8. The daily range of tide is abnormally diminished at Riverside and the shape of the tide curve is further distorted during the event.

Based on these observations, it is expected that during the highest seasonal river flows in the spring, the tide at Riverside would probably be completely masked for short periods. The computation of tidal datums using observations from the stations upriver from Newburyport during periods of high river flow would not be possible using NOS methods because of the masking of the tide and the lack of correlation of daily and monthly variations between Riverside and Newburyport. Figure 9 shows the high degree of correlation between the monthly mean sea level observed at Riverside and the monthly mean river discharge as measured at Lowell, Mass. from June through September 1989 (USGS, 1989). Figure 10 is a plot of the long term yearly river discharge measured at Lowell, Mass. and shows that the river flow for 1989 was about average for the time period 1969 - 89.

VIII. TIDAL PREDICTION

Two of the stations installed for this project are historical stations with published tidal differences from the NOS tidal prediction station at Portland (NOS Tide Tables, 1989). Table 6 is a comparison of the tidal differences found in Table 2 of the NOS Tide Tables and the differences computed using the time series observed for this project. The differences show no significant change in the time of tide at the Merrimack River Entrance from 1953 to 1989, however the range of tide is 0.3 foot less. The changes in times and height ratios at Newburyport both appear to be significant with the time of low water 18 minutes earlier and the range of tide 0.3 foot higher for 1989 than 1954. It is difficult to assess the cause of these differences. They are probably due to a combination of real changes due to dredging and natural changes in the estuary, and

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differences due to the different time series lengths and control stations used in computing the time and height differences for two different time periods.

Table 6 COMPARISON OF TIDAL DIFFERENCES AND CONSTANTS

Series	Table 2 Number	Name	Times High	Low	Height Ratio High	Low	Mean Range
1953	911	Merrimack R. Entr.	+0h20m	+0h24m	0.91	0.91	8.3
1989	911	Merrimack R. Entr.	+0h28m	+0h30m	0.88	0.88	8.0
1954	913	Newburyport	+0h31m	+1h11m	0.86	0.86	7.8
1989	913	Newburyport	+0h31m	+0h53m	0.89	0.89	8.1

Mean ranges in tenths of feet; time differences in hours and minutes from Portland. Height ratios referenced to the mean range at Portland.

Using standard NOS tide prediction methodology (Schureman, 1958 and Zetler, 1982), the harmonic constants found in Appendix 8 can also be used to predict the tide at each location. The harmonic constants provide a continuous predicted tide curve over desired time periods, rather than just the times and heights of the high and low waters as computed from the non-harmonic tidal differences found in Table 6.

Even though there are no major changes in the tidal differences from historical records, there are significant changes in the elevations of the tidal datums due to the different tidal epochs taking into account changes in relative sea level over the years.

The trend in relative sea level for the station at Portland, Maine, is estimated to be +0.006 foot per year for the period 1950 through 1986 (Lyles et al, 1988). Relative to arbitrary station datum, the mean sea level computed over specific NDTE's at Portland has risen 0.11 feet from the 1941-59 epoch to the 1960-78 epoch. Figure 11 is a dual plot of variations in monthly mean sea level and in yearly mean sea level at Portland. The elevations are referenced to the 19-year mean sea level for the 1960-78 NTDE. The monthly mean sea level curve provides the average variation in monthly mean sea level due primarily to seasonal wind and barometric pressure fields.

This relative apparent secular sea level rise is a combination of eustatic sea level change and vertical land movement. The contributions of each cannot be distinguished adequately at this time and is the subject of intense investigation by geophysical scientists.

IX.   SUMMARY

The Merrimack River Project is one of a series of cooperative projects between NOS and CENED covering estuaries within CENED district boundaries. This project, covering the lower tidal portion of the Merrimack River, Massachusetts, resulted in the collection of water level data from five separate locations on the river. At each of these locations, tidal datums have been computed, and tidal datum elevations published for a local network of tidal bench marks. Harmonic analyses have been run and sets of harmonic constants have been computed for each location for use in tidal prediction.

The most significant problem encountered during the project was the invalid low waters measured at Merrimacport for the first three months of the project due to the shallowness of the water. Use of a "bubbler" pressure gauge enabled collection of low waters for datum determination.

A secondary station was successfully operated at Newburyport during the project resulting in a 12-month time series. This station provided important information on the seasonal variation in tidal characteristics in the river and secondary datum control for the tertiary stations. The water level variations in the Merrimack River are due to a combination of: the transmission of the tide from the North Atlantic, through the river entrance, and up the river; the volume of river discharge coming downstream at any given time from the river drainage basin; and the transmission upstream of monthly and seasonal sea level variations due to long-term meteorological and climatological wind and barometric pressure fields.

The two lower river stations at Newburyport and Plum Island exhibit similar tidal characteristics over all time periods and are similar to outside characteristics. The effects of the river bed topography and river flow affect the three uppermost stations such that the typical tide curves are severely distorted by frictional and river flow effects. The tide is severely diminished at the uppermost stations during episodes of high river

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flow. Tidal datums in tidal rivers such as Merrimack River and the Connecticut River (NOS, 1989) are typically computed from data collected during the months of moderate to low river flow. Months of lower river flow provide the best correlation in monthly sea level to the outside primary control station and provide for a conservative Mean Lower Low Water chart datum for navigation purposes.

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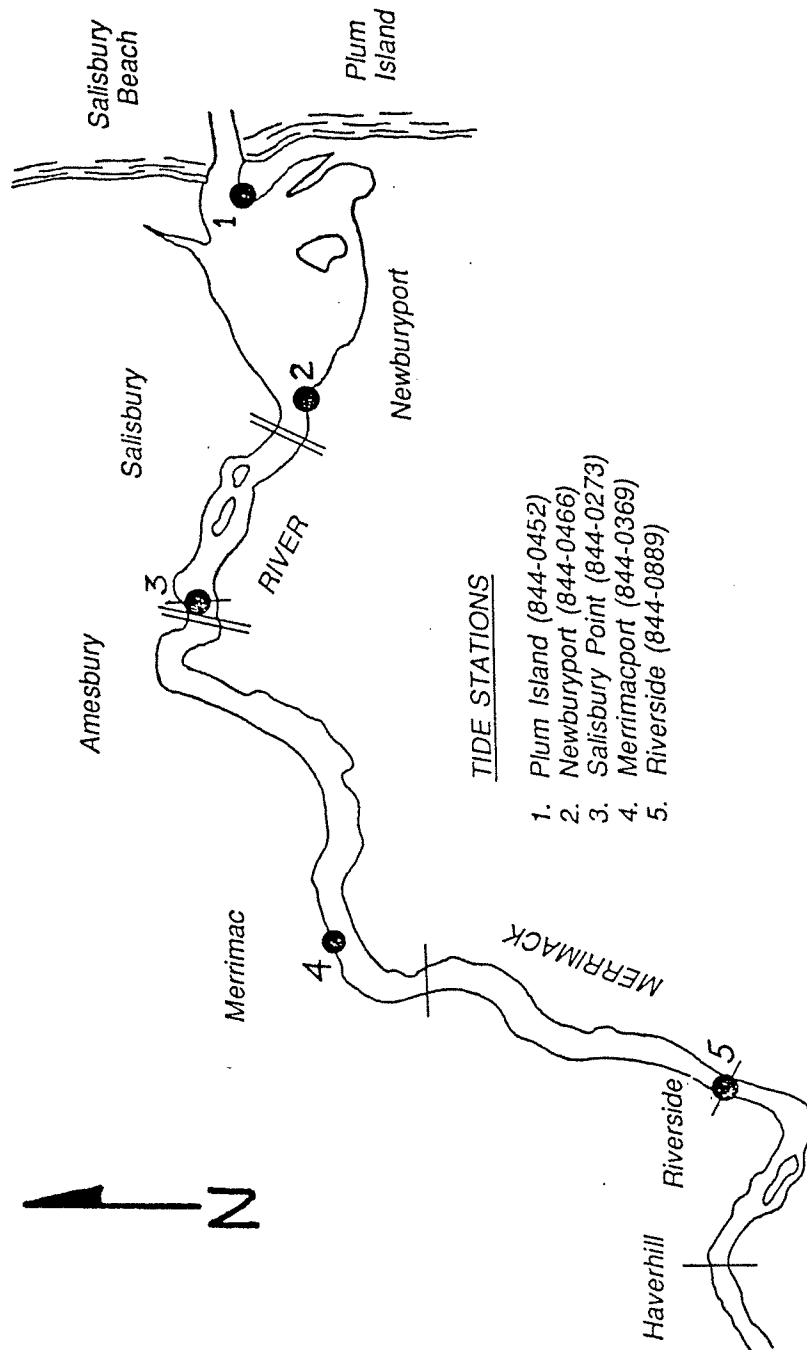
FIGURES

Figure 1. Tide Station Locations - Plum Island to Riverside
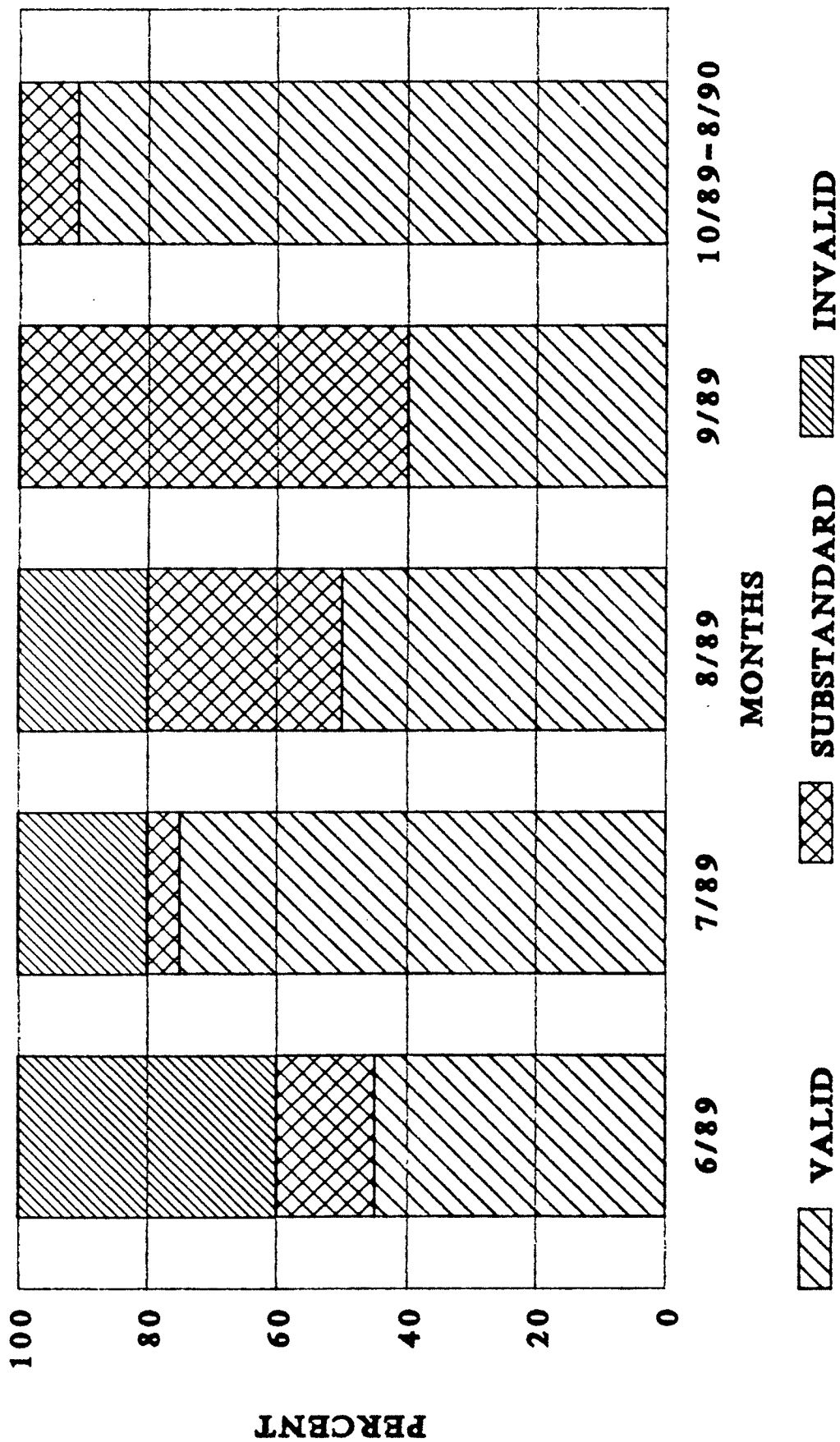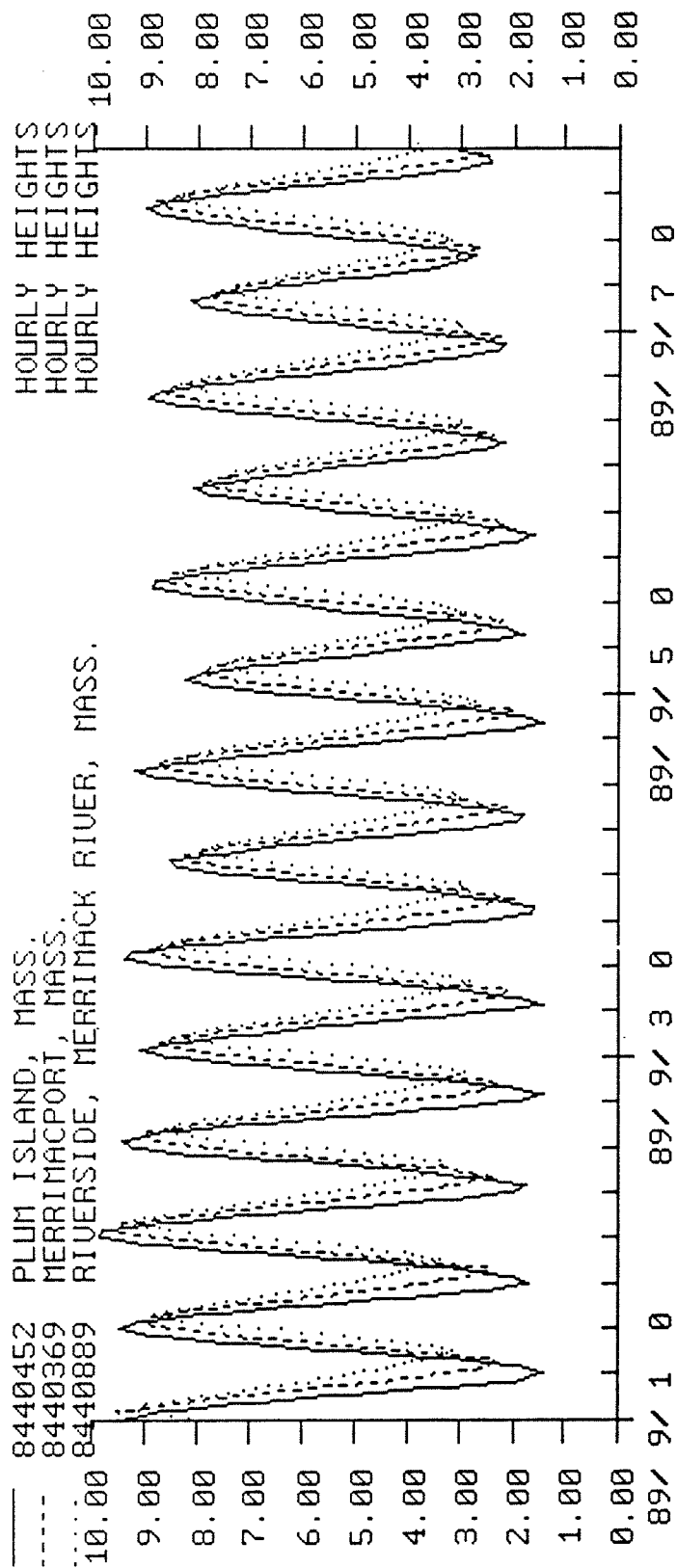
Figure 2. Overall Data Quality Classifications

Figure 3. Simultaneous Hourly Height Plot – Three Stations, Seven Day Window

84404852   PLUM ISLAND, MASS.
8440369   MERRIMACPORT, MASS.
8440889   RIVERSIDE, MERRIMACK RIVER, MASS.

HOURLY HEIGHTS
HOURLY HEIGHTS
HOURLY HEIGHTS
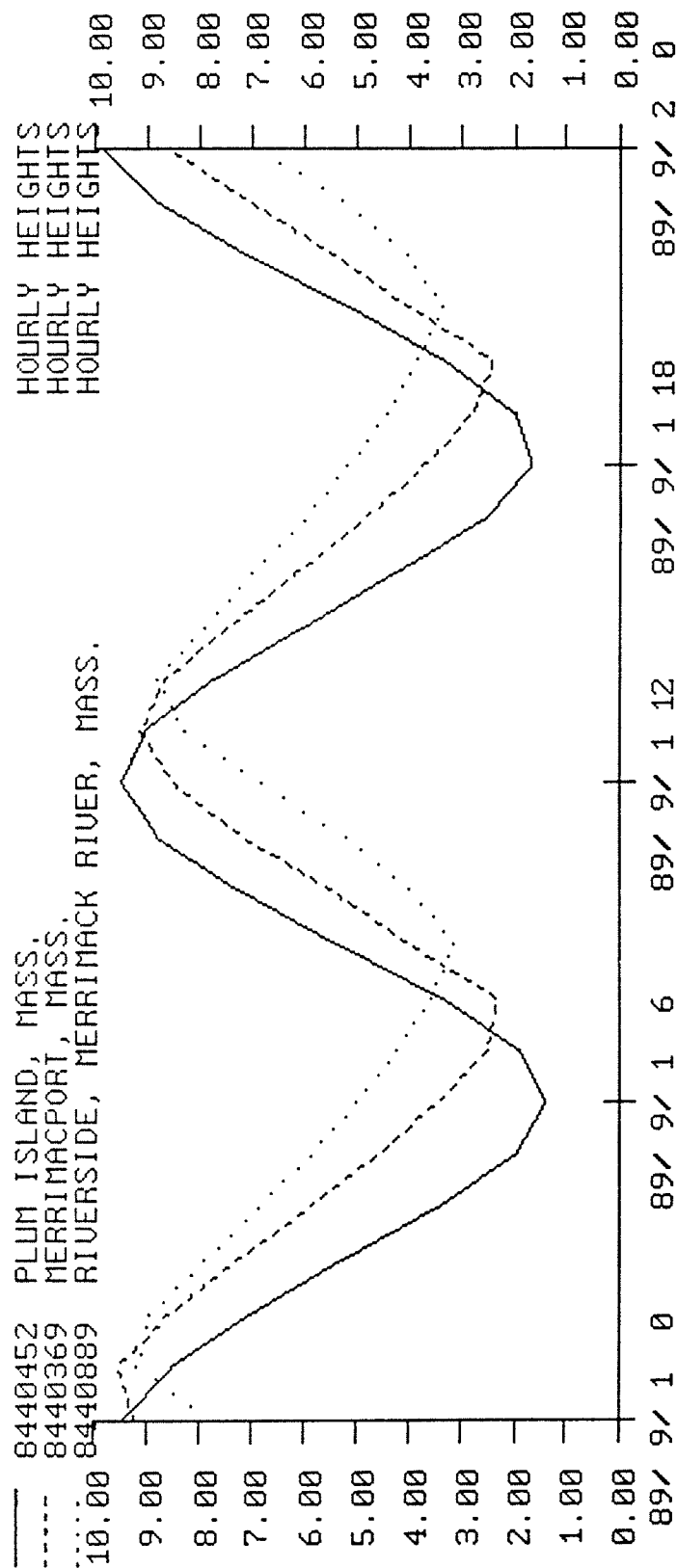
Figure 4. Simultaneous Hourly Height Plot — Three Stations, One Day Window

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RELATIONSHIP OF TIDAL DATUMS TO NGVD
MERRIMACK RIVER PROJECT

ELEVATION (FT) ABOVE NGVD

MILES UPRIVER FROM PLUM ISLAND

—△— MHW   —⊙— MSL   —+— NGVD   ····▽···· MLLW
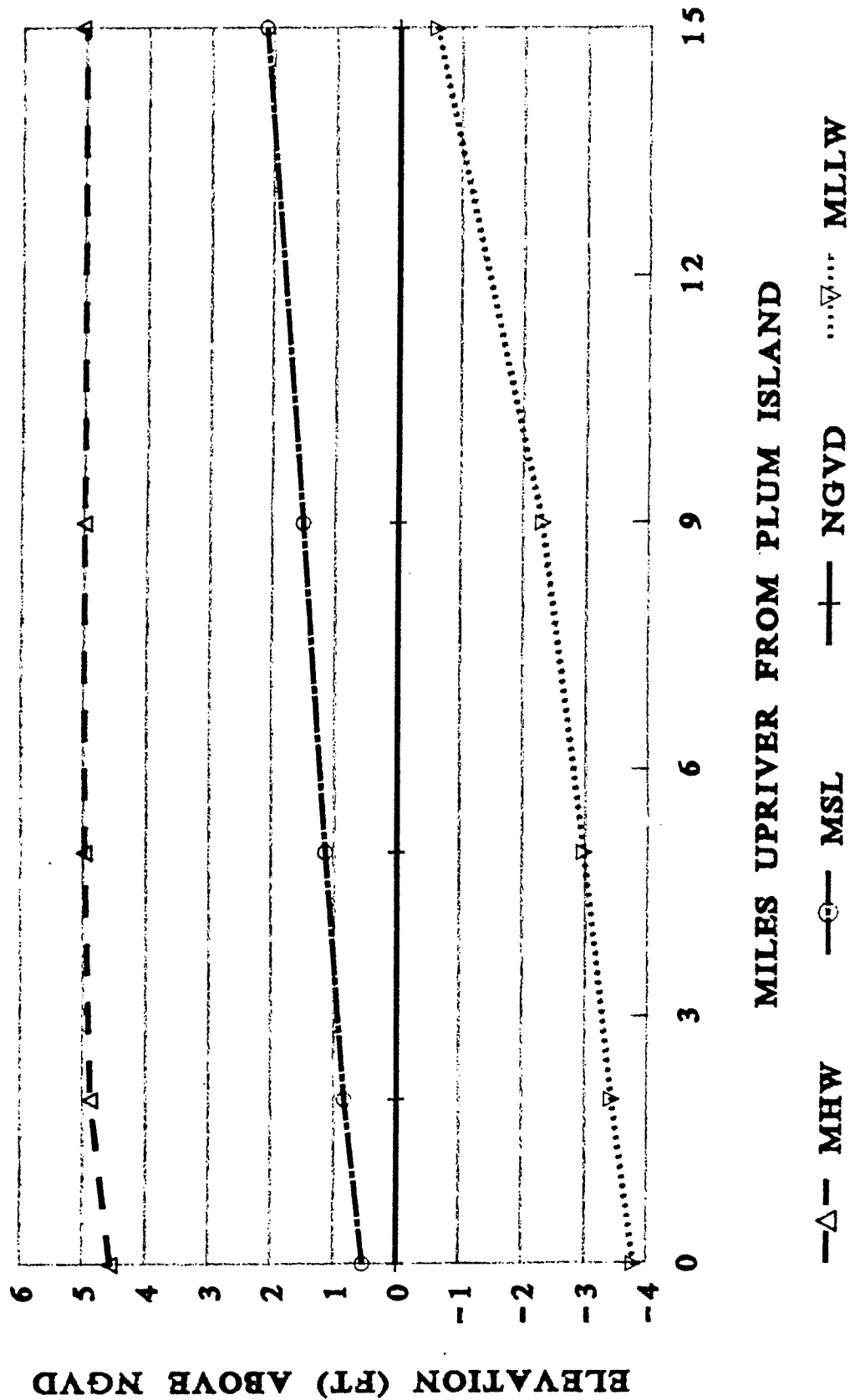
Figure 5. Relationship of Tidal Datums to NGVD

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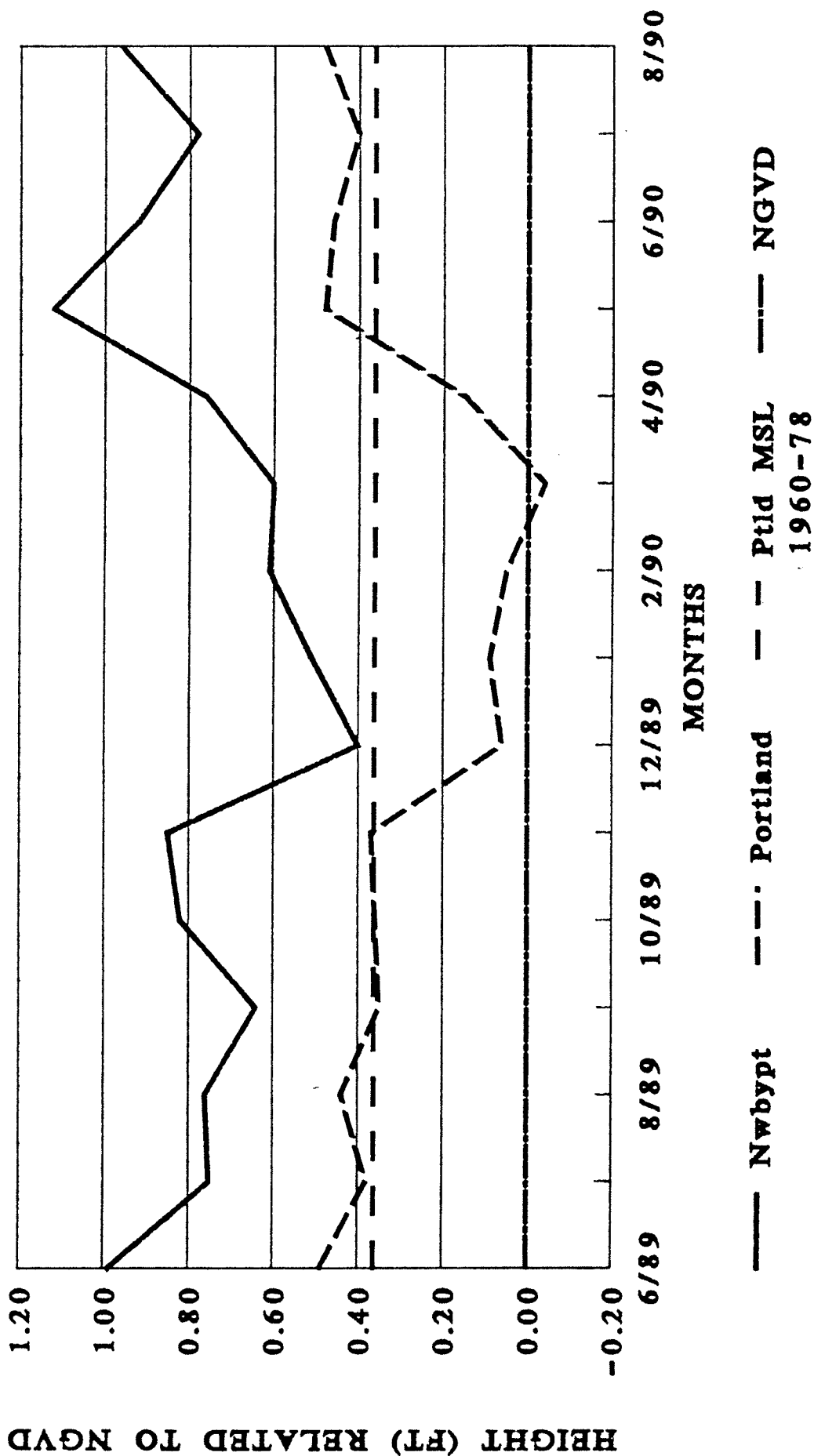
Figure 6a. Comparison of Monthly Mean Sea Level Between
Portland, ME and Newburyport, MA

MONTHLY MEAN RANGE OF TIDE
Portland, ME and Newburyport, MA

— Portland   — — Newburyport
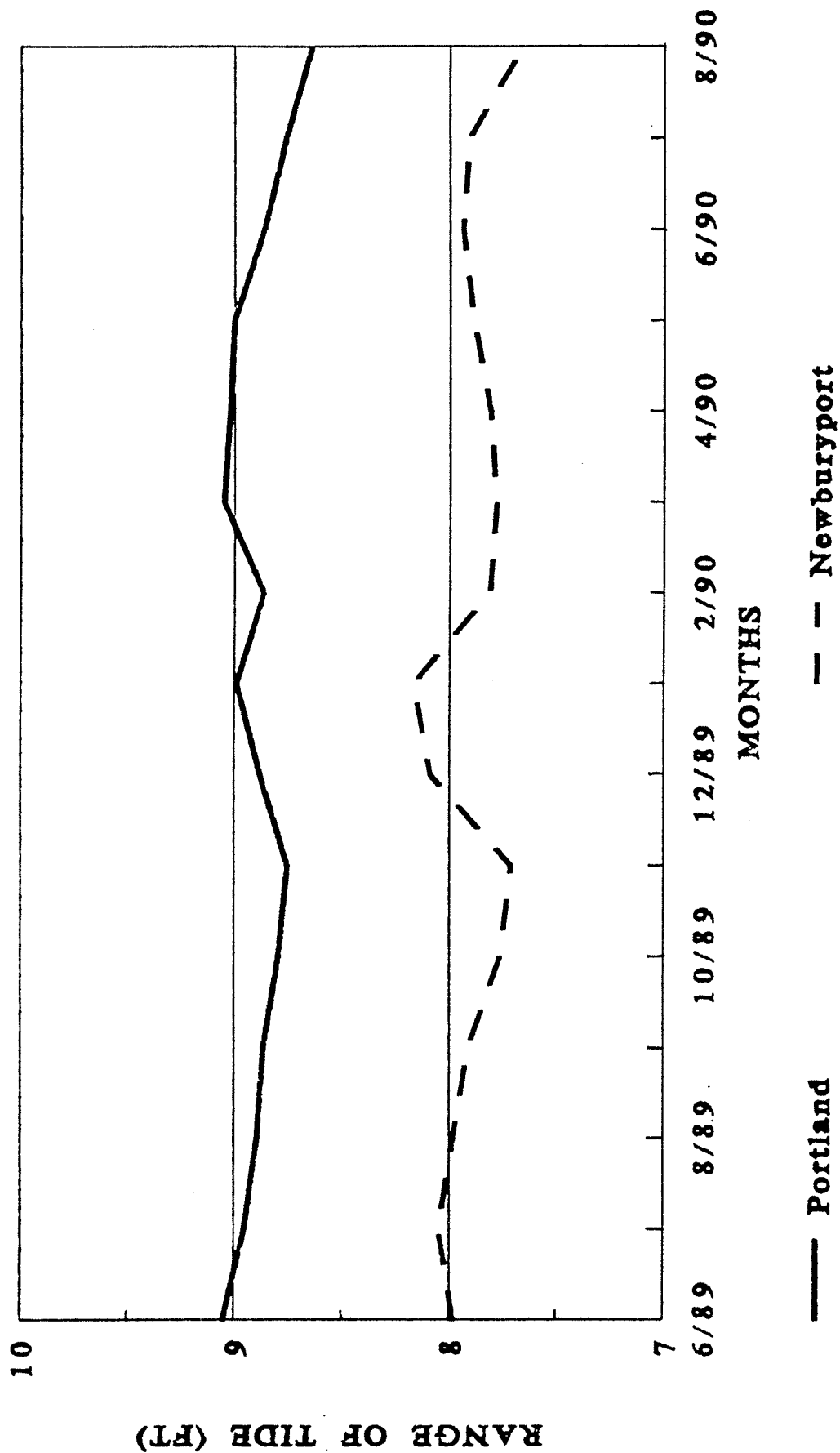
Figure 6b. Comparison of Monthly Mean Range of Tide Between
Porland, ME and Newburyport, MA
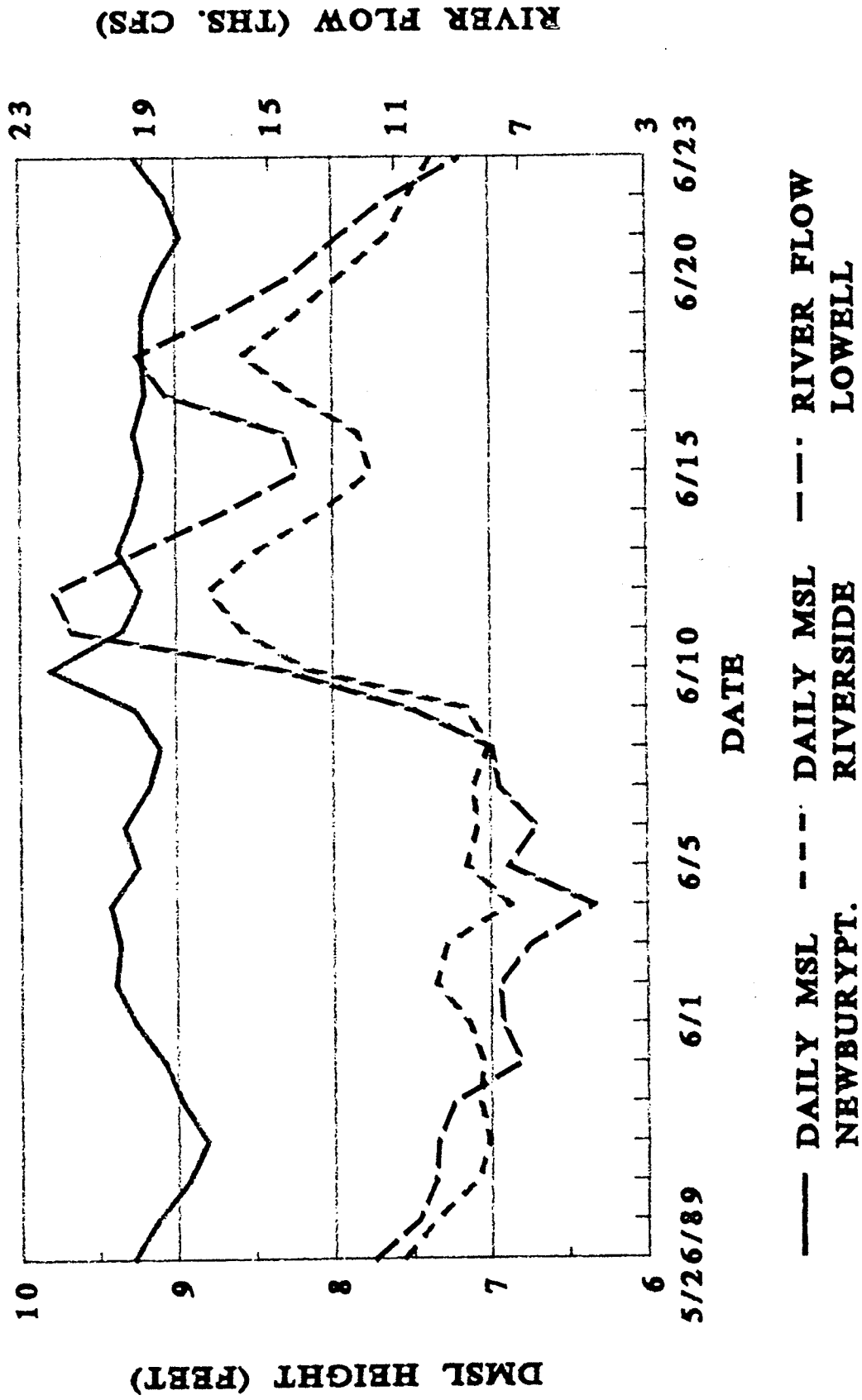
Figure 7. Comparison of Daily Mean Sea Level at Newburyport
and Riverside with Daily River Flow

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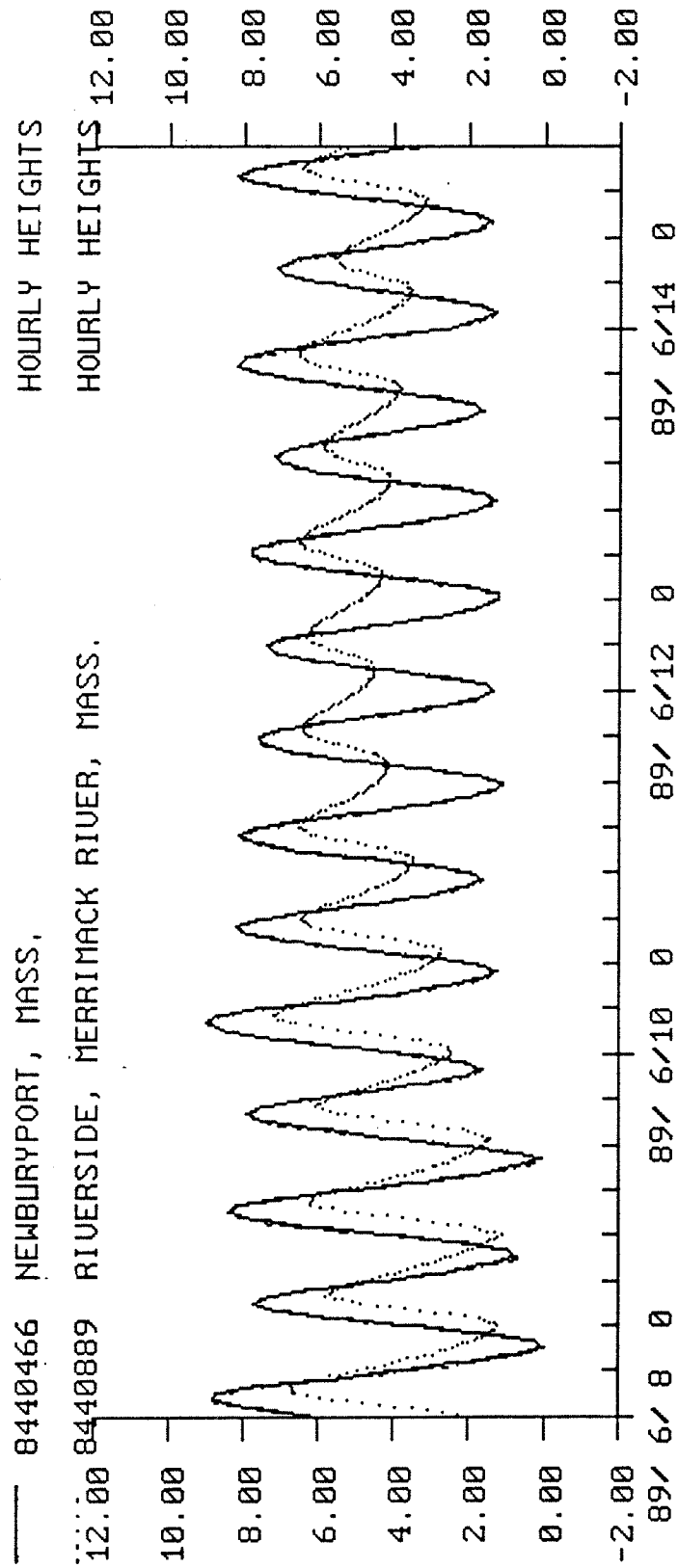
Figure 8.   Hourly Height Comparison During High River Flow - Seven Day Window

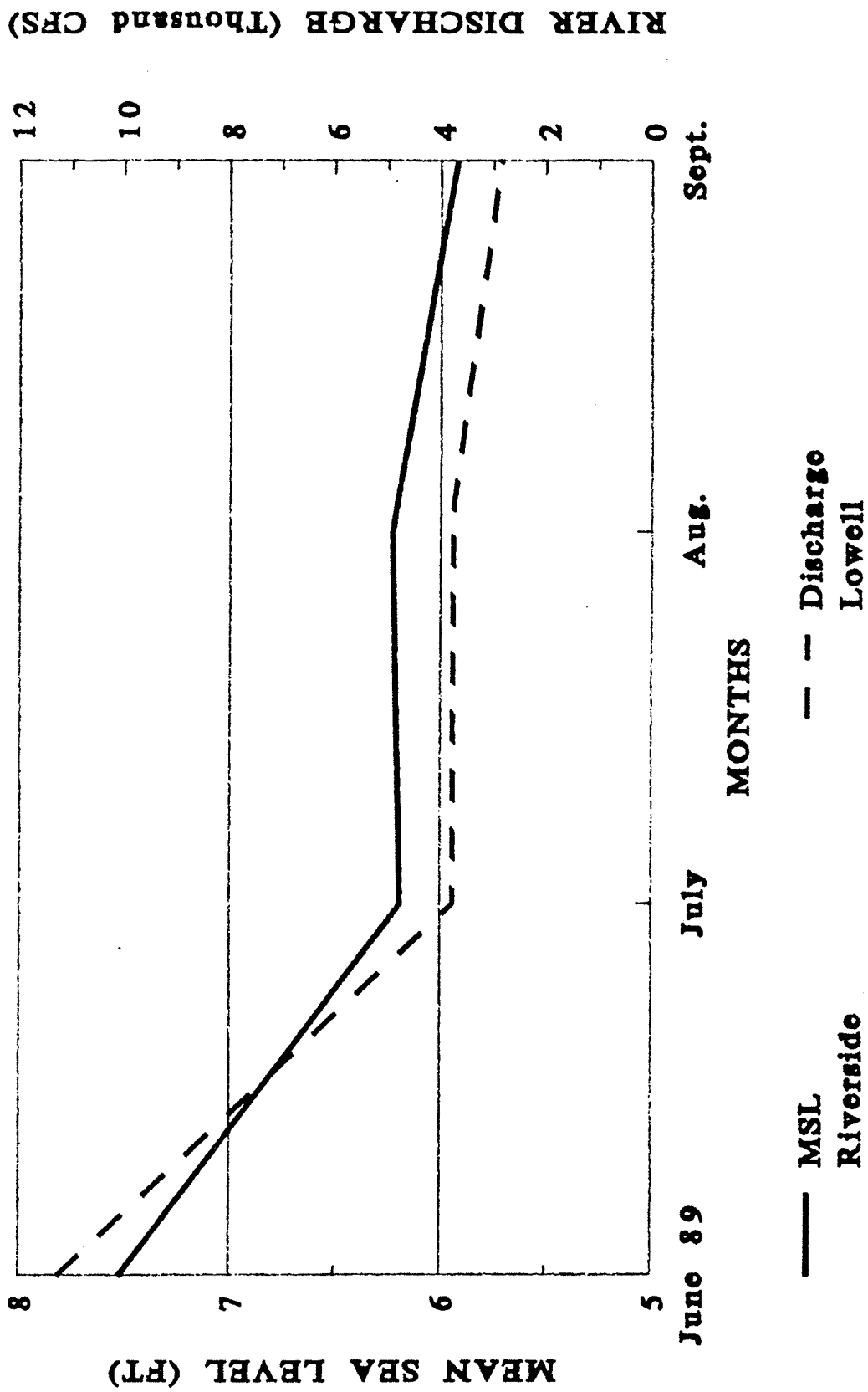29

MEAN SEA LEVEL VS. RIVER DISCHARGE
MERRIMACK RIVER

RIVER DISCHARGE (Thousand CFS)

MEAN SEA LEVEL (FT)

MONTHS

—— MSL
Riverside

— — Discharge
Lowell

Figure 9. Comparison of Monthly Mean Sea Level at Riverside
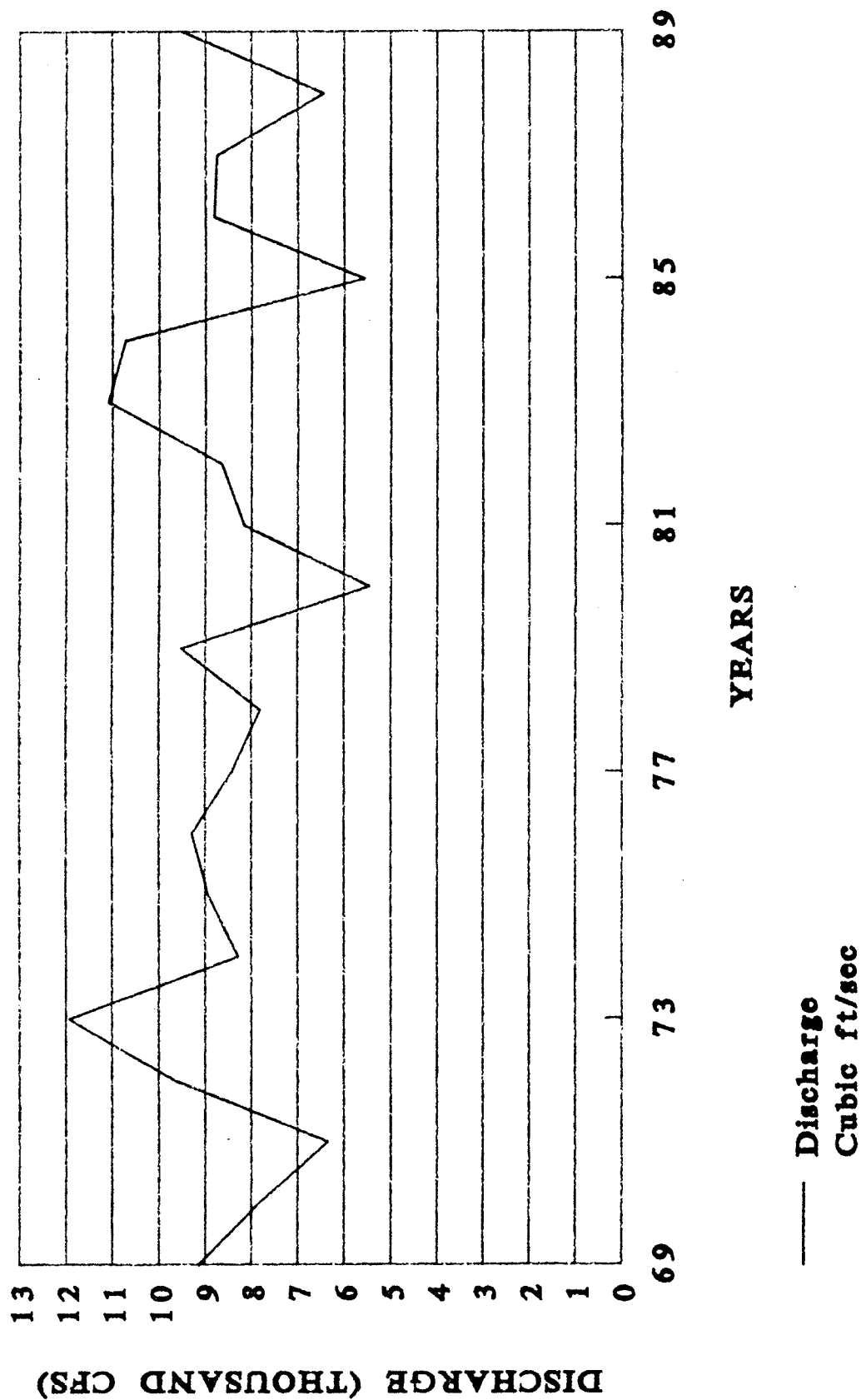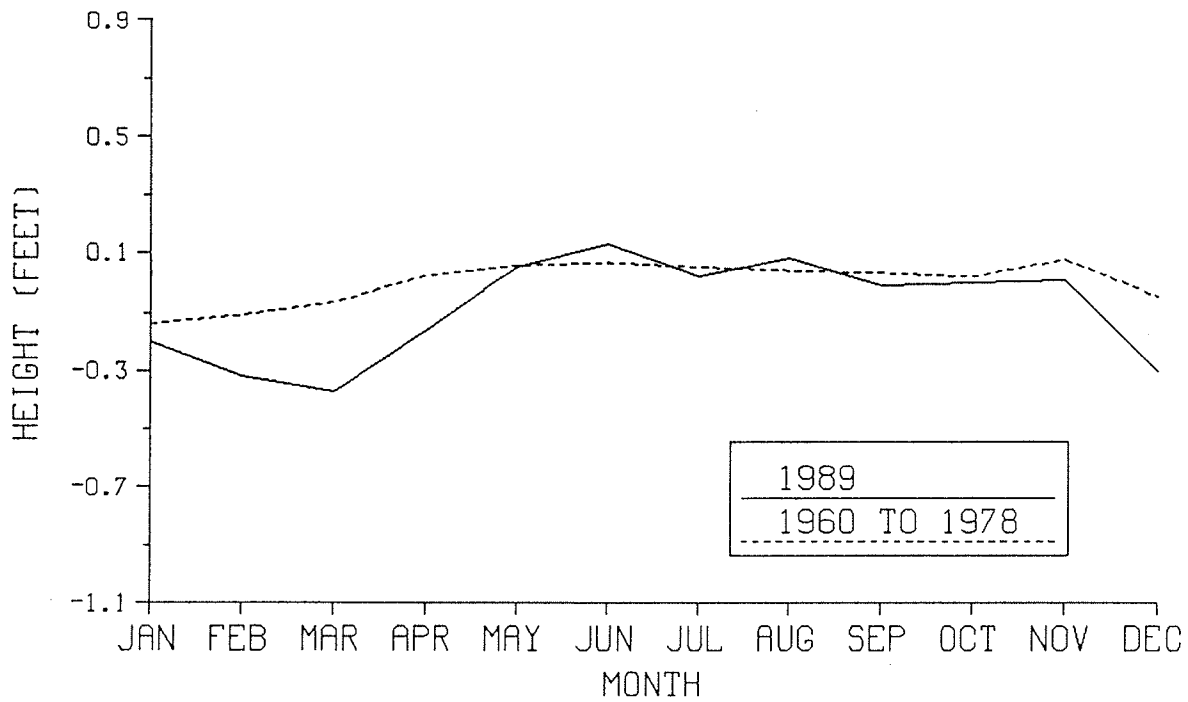and Monthly Mean River Discharge

Figure 10. Calendar Year Mean Discharge – Merrimack River at Lowell

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MONTHLY MEAN SEA LEVEL
STATION NO. 841-8150
PORTLAND, ME

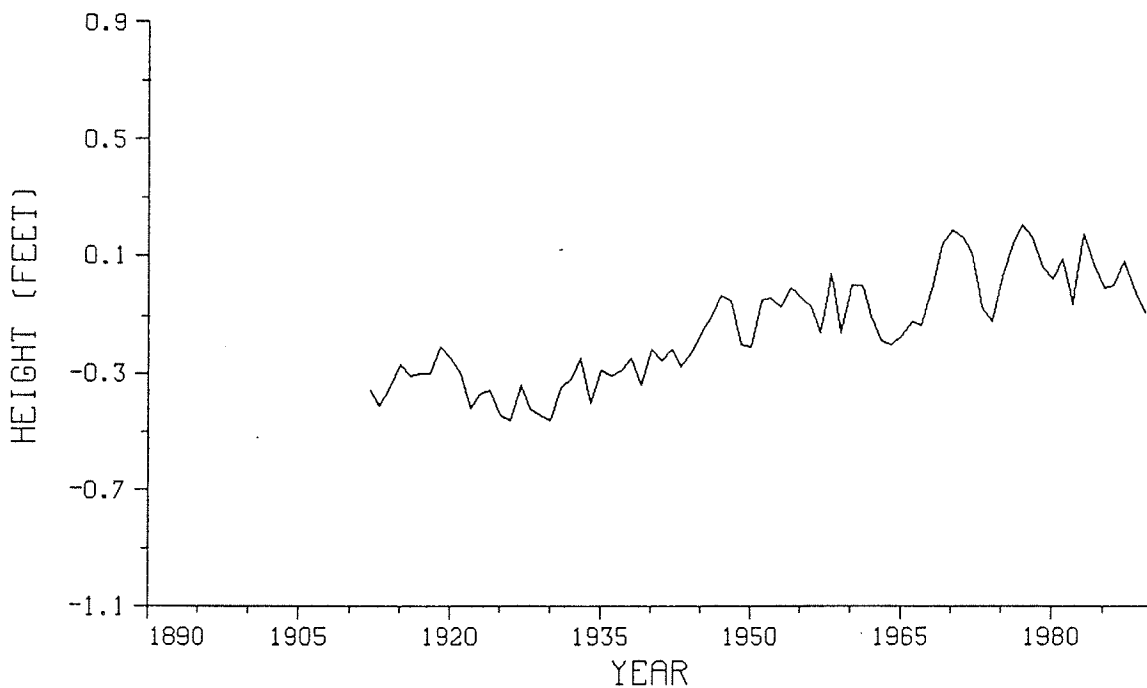YEARLY MEAN SEA LEVEL
STATION NO. 841-8150
PORTLAND, ME

Figure 11.   Monthly Mean Sea Level and Yearly Mean Sea Level
        for Portland, ME

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